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THE APPLICATION OF SEARCH THEORY  
TO THE TIMELY LOCATION OF  
TACTICAL BALLISTIC MISSILES

by

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Lieutenant, United States Navy  
B.S., University of Florida, 1985

Submitted in partial fulfillment  
of the requirements for the degree of

MASTER OF SCIENCE IN OPERATIONS RESEARCH

from the

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/, March 1993



## **ABSTRACT**

The application of search theory provides a systematic approach to the location and interdiction of mobile tactical ballistic missiles. Specifically, the use of an algorithm that employs a negative search to eliminate regions of an area based on terrain and road access is presented in this paper. Defense Mapping Agency digital terrain elevation data is used in conjunction with the algorithm to create probability maps of the search area. Included are five examples of this. With the search area reduced, several distribution functions are examined to simulate search time distribution needed for optimal allocation of search effort.

## **THESIS DISCLAIMER**

The reader is cautioned that computer programs developed in this research may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the programs are free of computational and logic errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.

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# **I. INTRODUCTION**

## **A. BACKGROUND**

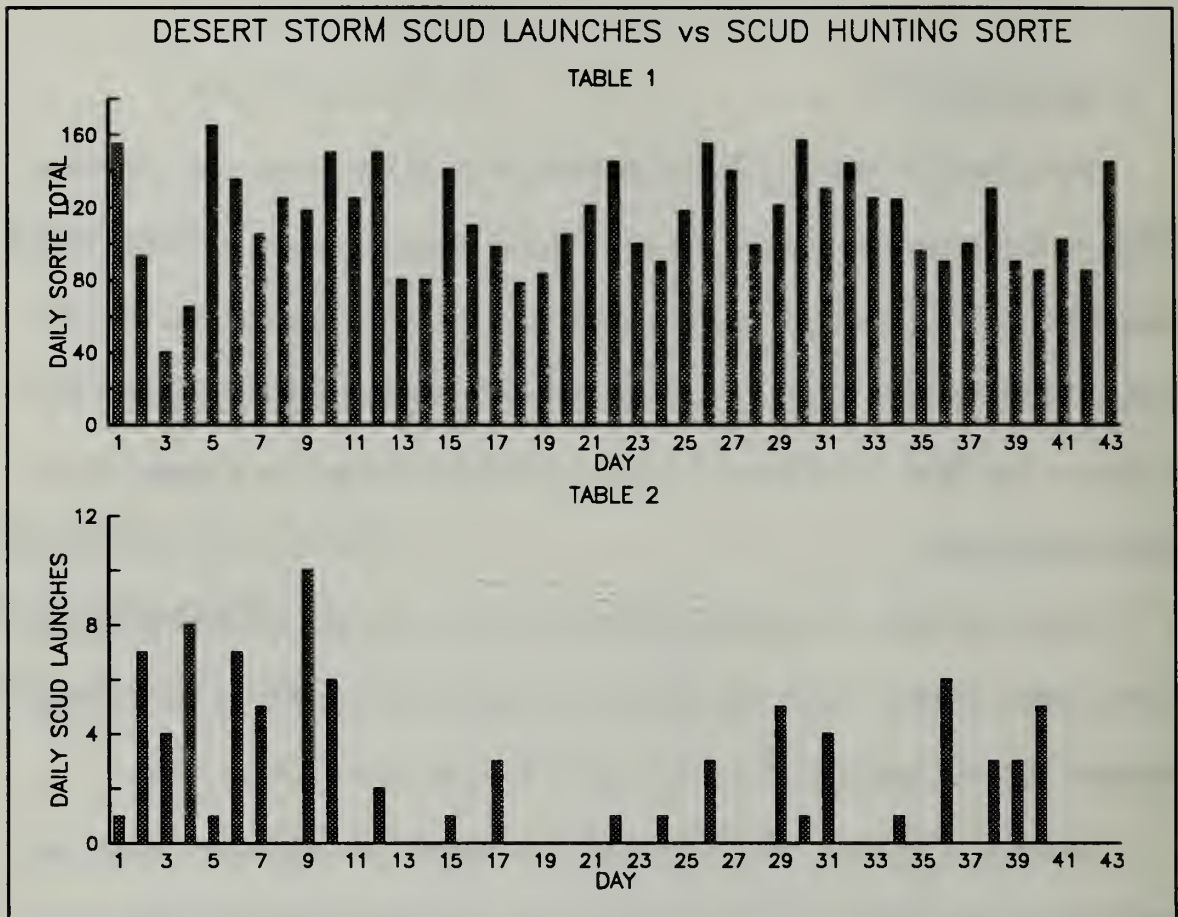
Tactical ballistic missiles (TBMs) and their associated transporter erector launchers (TELs) presently represent one of the most serious threats to world stability. These missiles are capable of delivering conventional, chemical or nuclear warheads to distant targets. The political and social ramifications of a conventional attack are evidenced from the Persian Gulf War. The effects of a nuclear or chemical attack on a major city are almost unfathomable.

Compounding the threat is the mobility and relative ease with which these missiles can be hidden, combined with the difficulty of tracking and destroying the incoming warheads. Effective mobile TBM defense must therefore address both problems.

Location of mobile TBM/TELs has been likened to submarine search and detection. In both cases a wide area search must be conducted for high-value, time-sensitive mobile targets using limited search resources. However, no effective doctrine has been developed to apply established techniques to the TBM problem. During the Persian Gulf War large numbers of tactical aircraft were employed to search out and destroy Soviet-made/Iraqi-modified Scud missiles. This counterforce strategy met with only limited success. Tables 1 and 2 show no tangible correlation between daily sortie total and the number of Scud missiles launched on that day. The overall decrease in missile launches could be related to the large number of sorties, but is most likely due to a



depletion in the stock of available missiles.



Tables 1 and 2.

Counterforce has worked well for the United States tactically, in the suppression of enemy air defenses (SEAD), and strategically, by targeting Soviet intercontinental ballistic missile (ICBM) fields for destruction in the event of a pre-emptive attack on the United States. It can also be applied to the problem at hand by creating an infrastructure that coherently combines search theory, search asset management, timely target location dissemination, and effective weapons delivery. Just as the operator of an Iraqi surface-to-



air missile battery or Russian ICBM crewman knows that the use of his weapon will bring swift retaliation, when the crew of a TBM/TEL know they stand a "good chance" of dying if they venture from cover to launch a missile it will become extremely difficult to motivate them to do so.

## **B. STATEMENT OF THESIS**

The application of search theory provides a systematic approach to the timely location of tactical ballistic missiles (TBMs) and their associated transporter erector launchers (TELs) prior to missile launch.

## **C. THE LIBYAN SCENARIO**

The following scenario is included to give the reader an understanding as to when, where and why a comprehensive TBM/TEL search might be initiated by the United States. Libya was chosen because it represents a tangible threat, data was readily available and the author feels that Iraq has been over-analyzed.

- 1) Libya acquires advanced long-range (+1000km) TBMs from China.
- 2) Tensions increase between the U.S. and Libya during a freedom of navigation exercise conducted in the Gulf of Sidra.
- 3) An incident occurs, shots are fired, and three Libyan fighters are downed.
- 4) In retaliation, Libya launches a TBM at the U.S. naval base in Naples, Italy. The missile is equipped with a chemical warhead manufactured at a Libyan pharmaceutical facility.
- 5) The USS Saratoga and its battlegroup are tasked to locate and destroy all TBM/TELs in the Tripoli area.

## **II. A TBM CIRCULATION MODEL**

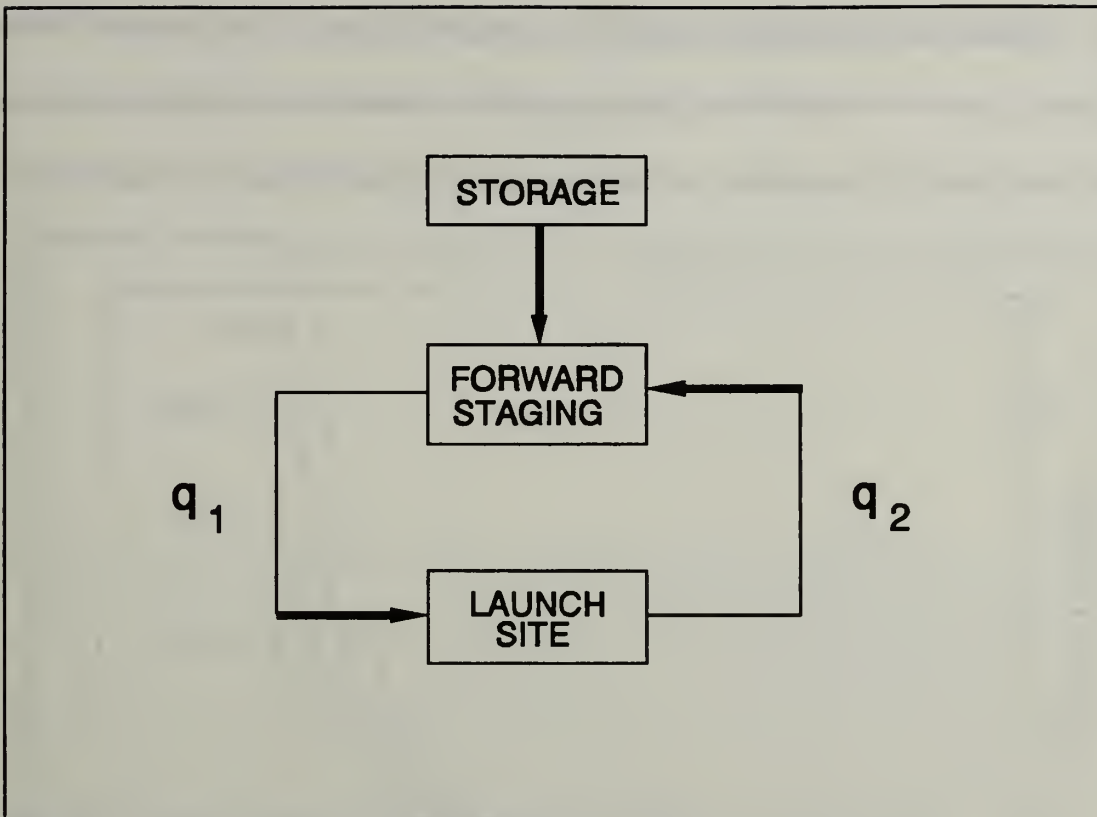
### **A. THE PROBLEM**

To create a systematic approach to locating and interdicting TBM/TELs a simple model is needed to highlight the benefits of prosecuting the mobile launcher in all phases of its employment. Current efforts to counter mobile TBMs are focused on the post-launch intercept of incoming warheads with sophisticated air defense systems such as PATRIOT and on prosecution of the mobile launcher after missile launch using rocket plume location cuing. While these are both viable methods of addressing the mobile TBM problem, they assume the problem begins after missile launch.

This chapter will introduce a circulation model formulated by Mark A. Ehlers in his September 1992 thesis [Ref. 1] that resembles one developed and analyzed by the Center for Naval Analyses in 1969. It will provide valuable insight into which phases of mobile TBM launch operations to focus on and also serve as a foundation for the pre-launch search strategies discussed in the next chapter.

### **B. A CIRCULATION MODEL**

Figure 1 shows a simple circulation model which approximates the movement of a transporter erector launcher during all phases of operation. It is assumed that during peacetime launchers will normally remain in a storage facility, occasionally deploying for proficiency training and system upkeep. During a crisis, the launchers may be covertly



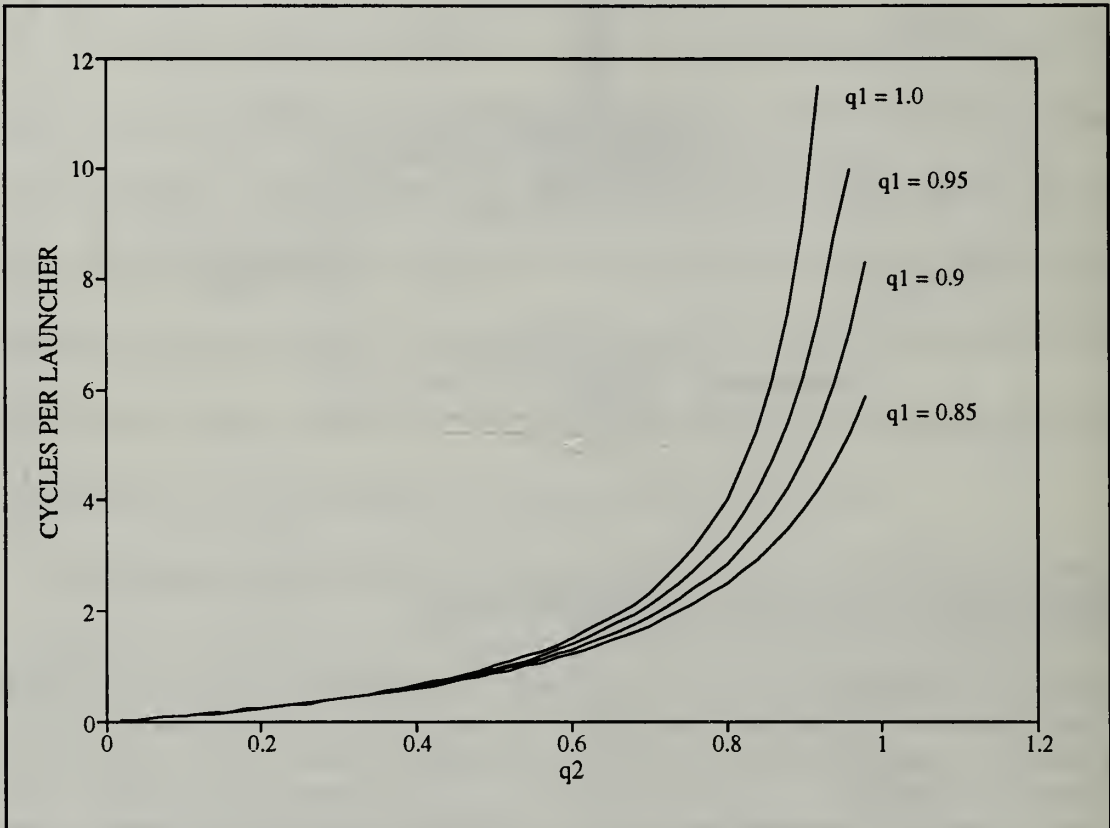
**Figure 1.** Mobile TBM Launcher Circulation Model

deployed to forward staging areas or remain at the original facility, using it as a staging area. With the commencement of hostilities, the launchers begin a cycle of movement from the staging areas to launch sites and then back to the staging areas for maintenance, re-arming, or further instructions.

A probability of survival for the launchers can be assigned to each leg of the cycle, represented by  $q_1$  and  $q_2$  respectively. This cycle will continue until either the launcher is destroyed, missile supply is depleted, or hostilities cease. Although this is a simple model, it can provide valuable insight on how best to prosecute the launchers during a given cycle.

### C. CIRCULATION MODEL RESULTS

Figure 2 shows the results of LT Ehlers' analysis of the circulation model. With the current focus of the mobile launcher counter effort centered on the post-launch rocket plume cuing tactic, little attention has been given to pre-launch search and interdiction.



**Figure 2.** Expected Missile Launches as a Function of  $q_2$ .

It is therefore reasonable to assume that the outbound launcher survival probability ( $q_1$ ) is 1.0. The  $q_1=1.0$  curve in Figure 2 shows that as  $q_2$  increases above about .6, the expected number of launches by launcher  $i$  before destruction begins to increase exponentially. This implies that if the rocket plume cuing tactic cannot achieve a  $0.35(1-q_2)$  probability of launcher kill, the expected number of missile launches will be unacceptably high. However, reducing  $q_1$  by just 10% ( $q_1=.9$ ) allows considerably more

leeway in the reduction of  $q_2$  to achieve the same results. All this points to a need to conduct the mobile launcher counter effort with equal vigor in trying to reduce  $q_1$ . The next chapter will look at a process for doing just that.



### **III. METHODOLOGY**

The key to any effective search strategy is to know where to look. This may be an oversimplification, but it does provide a starting point for defining a specific search strategy. To know where to look one must thoroughly define the object that is being searched for. How big is it? How fast can it move? Is it limited by terrain? Does it require periodic maintenance at known locations? In addition to the physical properties of the search object, the employment practices of the organization that operate it must be considered. Are command and control centralized? Are the operators highly trained? Is there a possibility of attack? Only when these questions are answered can an effective search strategy be formulated.

#### **A. DEFINING THE SEARCH OBJECT**

The MAZ-543 transporter erector launcher (TEL) [Fig. 3] is the primary launch and support vehicle for the SS-1B (Scud-A), SS-1C (Scud-B), and SS-12 (Scaleboard) surface-to-surface missiles. The vehicle is 12m long and with the missile it weighs 29,000kg. It has a crew of 4, is capable of 60kph on hard surfaces and has a range of 1500km. Its 525hp deisel engine and 8 wheel drive system allow it to operate over rugged terrain but at the expense of speed and range. The standard tactic employed with these mobile missile launchers is the "shoot and scoot" technique of driving off a main road, setting up and firing the missile, and then quickly dismantling and moving before



the launch vehicle can be targeted. Therefore, the TEL operators will in all likelihood avoid rugged terrain which would preclude quick movement from the launch area.

With the lack of sophisticated training and the military dictatorship present in Libya it is probably safe to assume that military units will be under centralized control. Therefore, the TEL operators are more likely to stay in the vicinity of communications nodes or maintenance facilities (e.g. areas where telephone lines cross major roads or military depots).



**Figure 3.** Maz-543 Scud Transporter Erector Launcher.

## **B. DEFINING THE SEARCH AREA**

The search area will be in the extreme northwestern corner of Libya in the vicinity of Tripoli. The region is defined by the rectangle with corners at 33-00N 012-00E, 33-00N 014-30E, 32-15N 012-00E, and 32-15N 014-30E and contains 23,400 square kilometers.

## **C. DEFINING THE PRE-LAUNCH SEARCH STRATEGY**

The initial idea for this thesis came about while I was on an experience tour at the Johns Hopkins University Applied Physics Laboratory in Columbia, Maryland during the summer of 1992. While there I was introduced to the problem of locating mobile TBMs in a hostile environment by the Naval Warfare Analysis Division (NWAD). It was suggested I try to create a search technique based on reducing the area to be searched by taking into account factors such as terrain, road access, vegetation and the physical limitations of the TEL vehicle. With these factors taken into account, large portions of the original search area would become completely unreachable, while others would be reachable only through great effort and time expenditure. The objective is to minimize the search area, thus maximizing both probability of detection and search asset usage. However, this does not mean the hard-to-reach areas can be completely ignored, only that limited search assets should be concentrated on the high probability areas.

This search strategy is sometimes called "Negative Search Theory". The ultimate purpose of this thesis is to demonstrate the feasibility of applying negative search theory to TBM/TEL location. To achieve this it must be possible to create an algorithm that

generates a probability density matrix of the search area based on factors related to the search object and the search area and then represents this matrix as a color grid map.

#### **D. DIGITAL MAP CREATION**

To create the matrix required for the color grid map Defense Mapping Agency (DMA) digital terrain elevation data (DTED) [Ref. 2] was obtained to form the initial datafile used in calculating the ruggedness of the terrain for the search area. This data is unclassified and available on CD-ROM. It supplies elevation measurements in meters above sea level for every 100m increment horizontally for all land areas of the earth's surface. The data is divided into cells one degree of latitude in height and one degree of longitude in width below 45N and above 45S, respectively. Outside of these bounds the width of each cell increases to two degrees of longitude to account for the decrease in spacing between lines of longitude near the poles. To cover the search area defined earlier, data from three cells was needed. For my work I chose to extract every tenth elevation reading, thus creating a datafile composed of elevation readings every 1km. Therefore, each square kilometer of the search area is defined by the elevation readings at its corners. The reason only every tenth reading was extracted was to make the datafile of a reasonable size (approximately 200k of memory).

With the datafile built, it was necessary to create an algorithm (PASCAL, see Appendix) to determine the overall slope or brokenness for each 1km grid square. To accomplish this an equation that describes these characteristics accurately and concisely is needed. Let  $S_{ij}$  be the terrain factor expressing the slope of grid square  $[i,j]$  and defined

by the formula

$$S_{ij} = \frac{2\sqrt{\frac{\sum x_i^2}{4} - \left(\frac{\sum x_i}{4}\right)^2}}{1000}$$

where  $x_i$  represents the corner elevation readings for grid square [i,j]. The portion of the formula contained within the radical is a measure of deviation from the mean elevation for the particular grid which is then multiplied by 2 to account for the elevation difference on either side of the grid mean. Since the elevation readings are in meters the formula must be divided by 1000 (1km = 1000m) to express the deviation as a percent of the whole. The result of each computation was then assigned to one of four categories based on the magnitude of their deviation and re-entered into an array of the same format as the original datafile. The four terrain categories are:

0 : Areas of water.

1 : Areas with a slope of less than 3% ( $S_{ij} < 30$ ).

2 : Areas with a slope of between 3% and 6% ( $30 \leq S_{ij} \leq 60$ ).

3 : Areas with a slope of greater than 6% ( $S_{ij} > 60$ ).

For reference, a slope of greater than 6% is equivalent to gradients found on mountain roads.

Next, the array was then transformed into a color grid matrix based on the terrain category for each grid square using an algorithm (C, see Appendix) run on a Silicon Graphics work station. The Silicon Graphics operating environment provides a much easier way to get hard copy color results. Figure 4 shows the result of this process.



To enhance the realism of the model a road network overlay was added to the datafile. This was accomplished by adding two additional categories to the four terrain categories. They are:

4 : Unimproved dirt surfaced roads.

5 : All-weather hard surfaced roads.

If a grid square contained a road its terrain factor was replaced with the appropriate road factor. If the grid square contained both types then it was given a factor of 5. Figure 5 shows the result of this process with Tripoli in the upper right center of the map.

The datafile used to create figure 5 now forms the basis for highlighting areas of high probability for the location of TEL vehicles. The C algorithm used to create previous color grid maps was modified to highlight all areas of less than 3% slope and within 5km of either road type. The results of this are shown in figure 6. It seemed reasonable to assume that when a TEL vehicle emerges from hiding it will spend the majority of its time on roads to increase its range and movement ability, and that if it did leave a road it would only be for a short period of time and only travel over relatively flat terrain. The longer the TEL vehicle remains in the open the higher the probability of its being detected. In addition, once the missile is launched U.S. national reconnaissance assets are likely to determine the launch location. With this in mind the TEL operator must return to a place of hiding quickly. He cannot do this if he is constrained by geography (i.e. far from a road or in very rough terrain). Figure 7 shows the same thing except areas of less than 6% within 5km of a road are highlighted.

The final map, Figure 8, illustrates the ability to highlight areas of extreme interest such as rocket plume location which could lead to a reduction in  $q_2$ . This will be dealt with in the next section.

Figures 6 and 7 are crude but they illustrate a very valuable point. Using existing databases, information about the search object, and logically excluding certain possibilities the area to be searched continuously can be greatly reduced. Reducing the search area will reduce  $q_1$  since the same search assets can now be applied over a smaller area.



## TERRAIN FACTOR MAP TRIPOLI, LIBYA

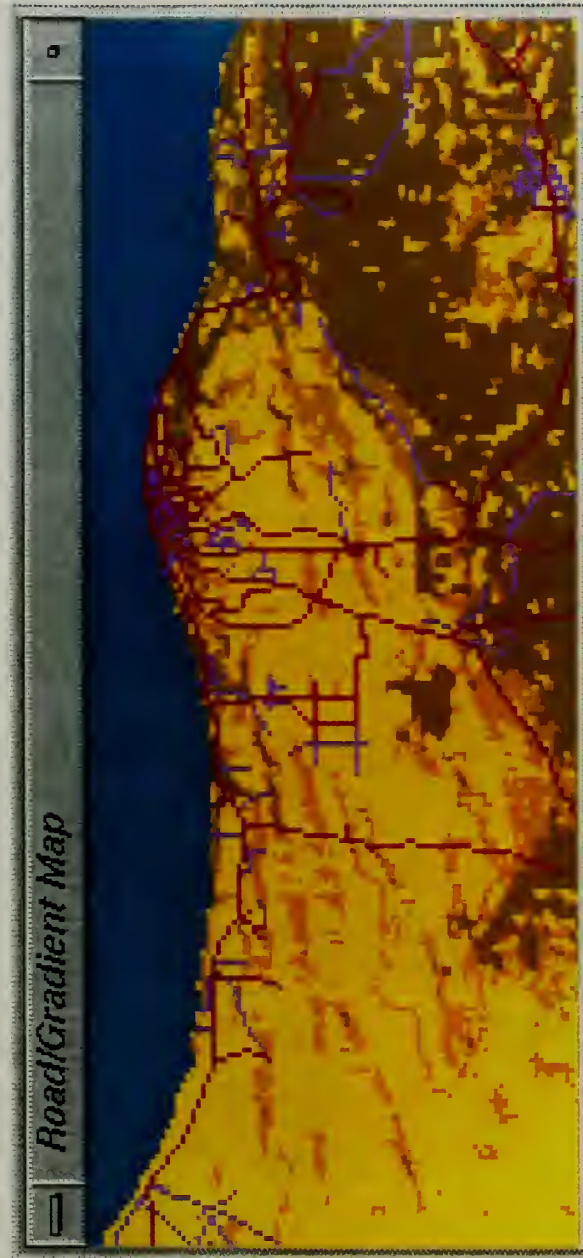
SLOPE KEY: YELLOW  $\leq 3\%$      $3\% < \text{TAN} < 6\%$     BROWN  $\geq 6\%$



FIGURE 4



**TERRAIN/ROAD FACTOR MAP TRIPOLI, LIBYA**  
**SLOPE KEY: YELLOW  $\leq 3\%$      $3\% < \text{TAN} < 6\%$     BROWN  $\geq 6\%$**   
**\*Road Key: Red = Hard-surface road**  
**Purple = Dirt road**



**FIGURE 5**



## TERRAIN/ROAD FACTOR MAP TRIPOLI, LIBYA

(5KM OVERLAY)

SLOPE KEY: YELLOW  $\leq 3\%$      $3\% < \text{TAN} < 6\%$     BROWN  $\geq 6\%$

\*Red Areas Indicate  $< 3\%$  Slope Within 5km of a Road



FIGURE 6





## TERRAIN/ROAD FACTOR MAP TRIPOLI, LIBYA

(5KM OVERLAY)

SLOPE KEY: YELLOW  $\leq 3\%$     $3\% < \text{TAN} < 6\%$    BROWN  $\geq 6\%$

\*Red Areas Indicate  $< 6\%$  Slope Within 5km of a Road

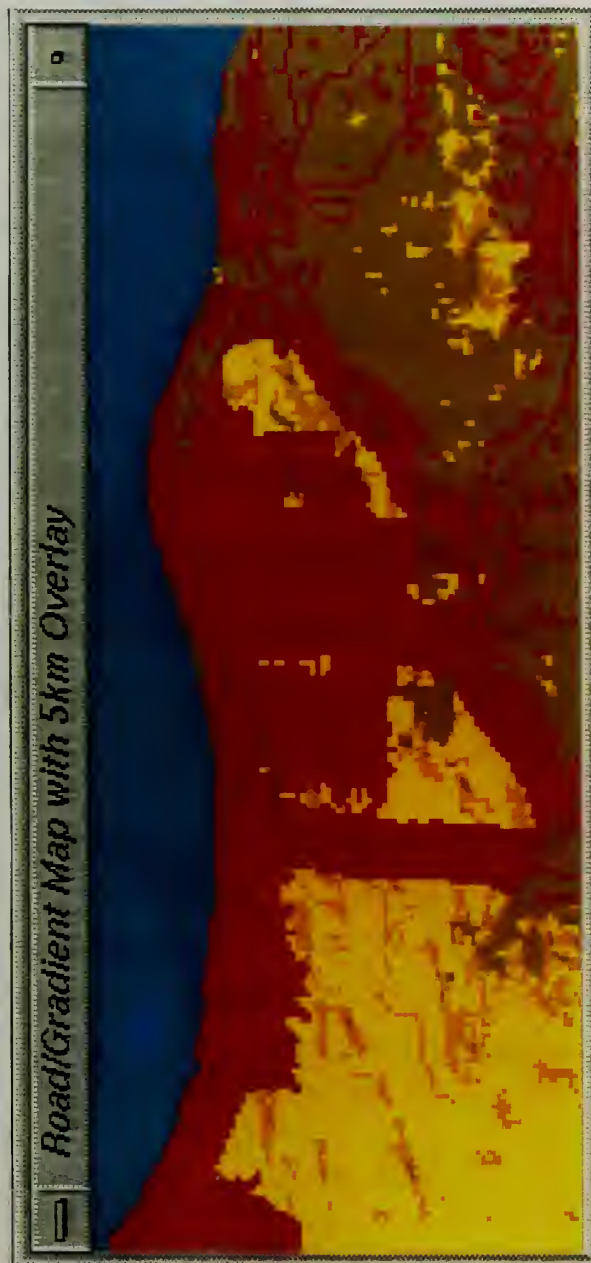


FIGURE 7



## TERRAIN/ROAD FACTOR MAP TRIPOLI, LIBYA

(5KM OVERLAY)

SLOPE KEY: YELLOW  $\leq 3\%$  3%  $< \text{TAN} < 6\%$  BROWN  $\geq 6\%$

\*Red Areas Indicate Slope Within 5km of a Road

\*Purple Areas Indicate Rocket Plume Location +15 minutes



FIGURE 8



## IV. RESULTS

### A. PRE-LAUNCH SEARCH ENHANCEMENT

The goal of the pre-launch search strategy is to reduce  $q_i$  as much as possible by reducing the total area needed to be searched. The previous chapter described the steps taken to reduce the search area and the results of that reduction will be presented in this section.

#### 1. Analysis of Pre-Launch Search Strategy

The following notation is used:

$p(i)=\text{Pr}\{\text{a launcher is in cell } i\}.$

$x_i=\text{the amount of effort placed in cell } i \text{ (aircraft minutes).}$

$E=\text{total search effort (aircraft minutes).}$

$n=\text{total number of cells in the search area.}$

$T_L=\text{total number of launchers in the search area.}$

$X=\text{time to find a launcher in a cell given one is present.}$

$F_i(x_i)=\text{Pr}\{\text{find launcher in cell } i \text{ expend effort } x_i \text{ and launcher is in cell } i\}.$

$L=\text{total number of launchers found after searching.}$

Therefore,

$$\text{Pr}\{X \leq x_i\} = F_i(x_i)$$

represents the probability a launcher is found in cell  $i$  for a given amount of search effort applied to cell  $i$ . Letting  $L_i=1$  if a launcher is found in cell  $i$  and 0 otherwise, then the





total number of launchers found is

$$L = \sum_{i=1}^n L_i$$

and

$$E[L] = \sum_{i=1}^n E[L_i] = \sum_{i=1}^n Pr\{L_i=1\}$$

where

$$Pr\{L_i=1\} = Pr\{X \leq x_i\} p(i)$$

for a vector of search effort  $\mathbf{x}=(x_1, x_2, \dots, x_n)$ . Therefore,

$$E[L] = \sum_{i=1}^n p(i) F_i(x_i) ,$$

and the value  $q_1$  will be reduced in accordance with

$$\begin{aligned} q_1 &= Pr\{not\ found\} + Pr\{found\} (1 - Pr\{destroy! found\}) \\ &= \frac{T_L - E[L]}{T_L} + \frac{E[L]}{T_L} (1 - d) = 1 - \frac{dE[L]}{T_L} \end{aligned}$$

where  $d$  is the probability that if a launcher is found then it is destroyed. Since this thesis is merely demonstrating a process for reducing  $q_1$  and data on destruction probability is either hard to obtain or unavailable, no specific value will be assumed for  $d$ . The problem of finding the optimal search effort vector  $\mathbf{x}$  becomes

$$\begin{aligned}
& \text{Maximize} && \sum_{i=1}^n p(i) F_i(x_i) \\
& \text{Subject} && \sum_{i=1}^n x_i \leq E \\
& && x_i \geq 0 \text{ for } (i=1, 2, \dots, n) .
\end{aligned}$$

Figure 7 is used to represent a probability map of missile launcher locations. All cells in the same colored area are assumed to have a common  $p(i)$ . The red highlighted areas represent regions of equally high probability; call this area  $G_1$  and let it contain  $n_1$  cells. The yellow and tan areas are combined and represent regions of equally low probability; call this area  $G_2$  and let it contain  $n_2$  cells. The brown areas represent regions of extremely low probability; call this area  $G_3$  and let it contain  $n_3$  cells. Now let

$$\begin{aligned}
p(i) &= p_1, & \text{for every } i \in G_1, \\
p(i) &= p_2, & \text{for every } i \in G_2, \\
p(i) &= p_3, & \text{for every } i \in G_3,
\end{aligned}$$

where the areas are constructed so that

$$1 > p_1 > p_2 > p_3 > 0 .$$

The problem now simplifies to

$$\begin{aligned}
& \text{Maximize} && p_1 \sum_{i \in G_1} F_i(x_i) + p_2 \sum_{i \in G_2} F_i(x_i) + p_3 \sum_{i \in G_3} F_i(x_i) \\
& \text{Subject} && \sum_{i=1}^n x_i \leq E \\
& && x_i \geq 0 \text{ for } (i=1, 2, \dots, n) .
\end{aligned}$$

Now assume all cells of the same region have a common search time distribution function where

$$\begin{aligned}
F_i(x) &= H_1(x) & \text{for every } i \in G_1, \\
F_i(x) &= H_2(x) & \text{for every } i \in G_2, \\
F_i(x) &= H_3(x) & \text{for every } i \in G_3,
\end{aligned}$$

and the problem simplifies further to

$$\begin{aligned}
&\text{Maximize } p_1 \sum_{i \in G_1} H_1(x_i) + p_2 \sum_{i \in G_2} H_2(x_i) + p_3 \sum_{i \in G_3} H_3(x_i) \\
&\text{Subject } \sum_{i=1}^n x_i \leq E \\
&\quad x_i \geq 0 \text{ for } (i=1, 2, \dots, n).
\end{aligned}$$

Since the probabilities,  $p(i)$ , for each cell within a region are assumed to be equal and the characteristics (area and terrain factor) of each cell within a region are also equal, then it would seem the search effort for the region should be divided evenly. To prove this assume that all  $x_i$  within a region are equal to  $x$ . If the graph of search time distribution is concave, then

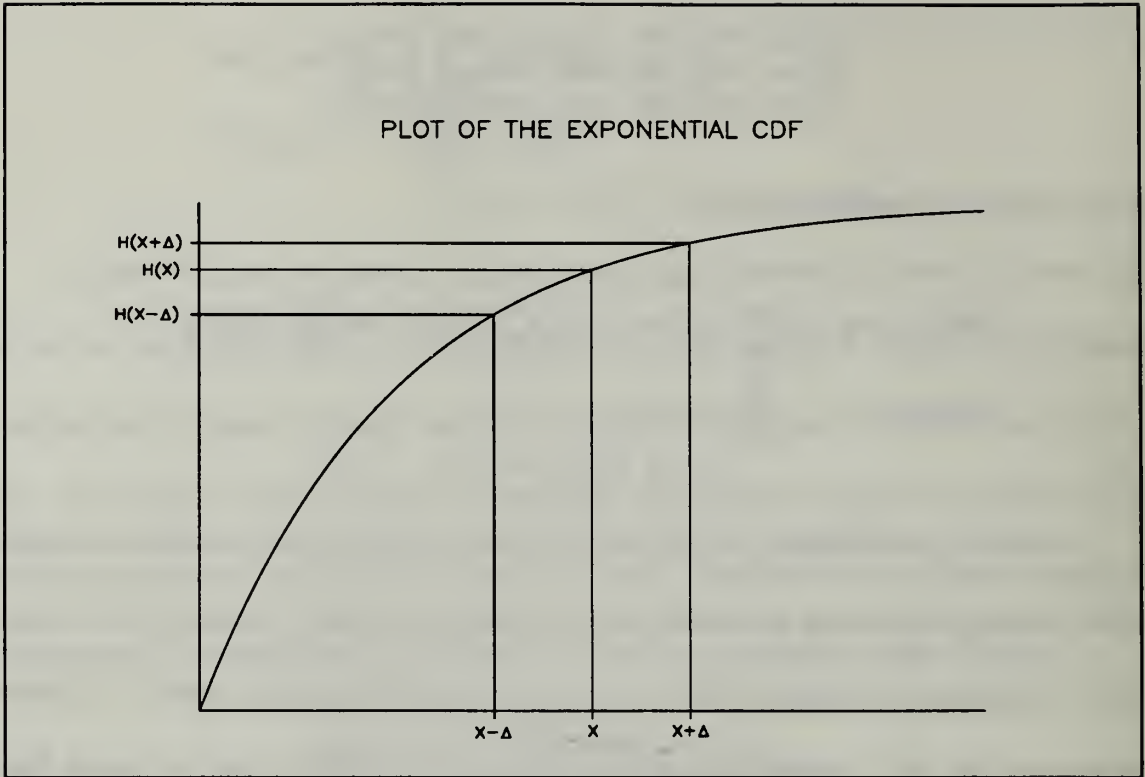
$$\begin{aligned}
H(x+\Delta) - H(x) &\leq H(x) - H(x-\Delta) \\
2H(x) &\geq H(x+\Delta) + H(x-\Delta)
\end{aligned}$$

and therefore dividing the search effort evenly within a region will yield the best result.

Figure 9 graphically depicts this. The distributions to be examined will, for the most part, satisfy this criteria. Therefore let

$$\begin{aligned}
x_i &= x_1 & \text{for all } i \in G_1 \\
x_i &= x_2 & \text{for all } i \in G_2 \\
x_i &= x_3 & \text{for all } i \in G_3.
\end{aligned}$$

The problem can now be expressed in its final form,



**Figure 9.** Argument for equal division of effort.

$$\begin{aligned}
 & \text{Maximize} && n_1 p_1 H_1(x_1) + n_2 p_2 H_2(x_2) + n_3 p_3 H_3(x_3) \\
 & \text{Subject} && n_1 x_1 + n_2 x_2 + n_3 x_3 \leq E \\
 & && x_1, x_2, x_3 \geq 0.
 \end{aligned}$$

Solving this constrained optimization problem yields the best allocation of effort for each cell within a given region. That is,  $x_i$  will be the amount of search effort placed in each cell of region  $G_i$ ,  $i=1,2,3$ . Clearly these values will depend on the search time distributions for  $H_1(x_1)$ ,  $H_2(x_2)$ ,  $H_3(x_3)$ . To determine these would require extensive testing with aircraft and objects approximating the search object performed in an environment that simulates the actual conditions of a search. This is well beyond the scope of my thesis, so it is proposed several possible cases be examined. Specifically, the uniform, exponential, and gamma distribution functions of time to find a launcher are examined.



### a. The Uniform Case

If the search time distribution is assumed to be uniform, then

$$H_1(x) = \begin{cases} \frac{x}{m} & 0 \leq x \leq m \\ 1 & m \leq x, \end{cases}$$

where  $m$  is the time needed to find the search object with certainty within a cell.

The problem now becomes

$$\begin{aligned} \text{Maximize} \quad & n_1 p_1 \left( \frac{x_1}{m} \right) + n_2 p_2 \left( \frac{x_2}{m} \right) + n_3 p_3 \left( \frac{x_3}{m} \right) \\ \text{Subject} \quad & n_1 x_1 + n_2 x_2 + n_3 x_3 \leq E \\ & 0 \leq x_1 \leq m \\ & 0 \leq x_2 \leq m \\ & 0 \leq x_3 \leq m. \end{aligned}$$

This linear program (LP) simply allocates as much effort as possible to search each cell of region  $G_1$  without breaking the constraints and applies the remainder (if any) to region  $G_2$  and possibly  $G_3$ . The solution follows:

1) Find  $E/n_1$ .

2) a. If  $E/n_1 \leq m$ , then the LP is solved with  $x_1^* = E/n_1$ ,  $x_2^* = x_3^* = 0$  and

$$E_L^* = p_1 E/m.$$

b. If  $E/n_1 > m$ , set  $x_1^* = m$  and find  $R_1 = (E - n_1 m)$ .

3) a. If  $R_1/n_2 \leq m$ , then the LP is solved with  $x_1^* = m$ ,  $x_2^* = R_1/n_2$ ,  $x_3^* = 0$  and

$$E_L^* = n_1 p_1 + p_2 R_1/m.$$

b. If  $R_1/n_2 > m$ , then find  $R_2 = (R_1 - n_2 m)$ .

4) a. If  $R_2/n_3 \leq m$ , then the LP is solved with  $x_1^* = m$ ,  $x_2^* = m$ ,  $x_3^* = R_2/n_3$  and

$$E_L^* = n_1 p_1 + n_2 p_2 + p_3 R_2/m.$$

b. If  $R_2/n_3 > m$ , then there is a surplus of effort  $(E - (n_1 + n_2 + n_3)m)$ .

This model is very insensitive to intelligence estimates; intelligence being the values placed on  $p_1$  and  $p_2$  by estimating the number of launchers in each region. All that need be known is the rank order of the probability regions to determine search effort allocation, i.e.  $p_1 > p_2 > p_3$ . By design,  $p_1 > p_2 > p_3$ . However, the expected number of launchers found is completely dependent on the probabilities assigned to each region.

Referring again to the map in Figure 7, it contains a total of 23,040  $1\text{km}^2$  cells of which 4,671 are water (blue). This leaves 18,369 land cells to be divided into the three categories mentioned previously. Region  $G_1$  (red) contains  $n_1=7,962$  cells, region  $G_2$  (yellow and tan) contains  $n_2=5365$  cells, and region  $G_3$  (brown) contains  $n_3=5042$  cells.

If  $E/X=1$  minute, the expected time to find a launcher in a cell given one is present, then  $m=2$ . Let the number of launchers being searched for be  $T_L=100$ , with an *a priori* estimate (based on intelligence) of the number of launchers being 75, 20, and 5 for regions  $G_1$ ,  $G_2$ , and  $G_3$  respectively, and a total search effort of  $E=10,000$  minutes.

Substituting in the appropriate values yields

$$\begin{array}{ll}
 \text{Maximize} & 37.5x_1 + 10.0x_2 + 2.5x_3 \\
 \text{Subject} & 7962x_1 + 5365x_2 + 5042x_3 \leq 10000 \\
 & x_1 \leq 2 \\
 & x_2 \leq 2 \\
 & x_3 \leq 2.
 \end{array}$$

The objective function value is 47.1 launchers found with  $x_1=1.256$ ,  $x_2=0$ ,  $x_3=0$ . Therefore,  $q_1=1-0.471d$  which, depending on the value assigned to  $d$ , could be a significant reduction. Interpreting this, if 10,000 minutes of search effort are to be used

to search for 100 launchers located within 18,369km<sup>2</sup>, then allocate 1.256 minutes to each cell of region  $G_1$  and nothing to the other regions. Note also that  $x_1=1.256=10000/7962=E/n_1 \leq (m=2)$ .

This optimal solution is not unique since the graph of the uniform distribution is neither concave nor convex but linear. However, it does evenly divide the search effort within all cells of the same probability region simplifying the searcher's ability to accomplish the mission.

Additionally, confidence limits can be placed on the number of launchers found if all the  $L_i$  are assumed to be independent in addition to the previous assumptions that all the  $x_i$  and  $p(i)$  are equal for each region. With these assumptions  $L$  is binomial with parameters  $n$  and  $H(x)p$  where  $E[L]=nH(x)p$  and  $Var[L]=nH(x)(1-H(x))p$ . So in region  $G_1$  the distribution is binomial with parameters  $B(n_1=7962, H_1(x)p_1=0.0118)$  and there is no distribution for region  $G_1$  to consider. Since  $n$  is large and  $H(x)p$  is small, this distribution can now be approximated by the Poisson distribution with parameters  $P(47.1)$ . This in turn can be approximated by the normal with parameters  $N(\mu=47.1, \sigma=47.1)$ . The 95% confidence limits for the normal distribution are readily calculable, with resulting bounds of  $33.65 < L < 60.55$ .

### **b. The Exponential Case**

If the search time distribution is assumed to be exponential, then

$$H_1(x) = 1 - e^{-\lambda x},$$

where

$$E[X] = \frac{1}{\lambda}.$$

As in the uniform case assume  $E[X] = 1$  minute, which implies  $\lambda = 1$ . In addition, since the probability a launcher is in region  $G_3$  is small by assumption and only a limited amount of search effort is available,  $p_3$  will be assigned a value of zero and the total number of launchers for which we are searching is reduced to  $T_L=95$ . This eliminates the third term of the original problem, simplifying further analysis.

Expressing  $x_2$  in terms of  $x_1$ ,

$$x_2 = \frac{E - n_1 x_1}{n_2}.$$

The problem now becomes

$$\begin{array}{ll} \text{Maximize} & L = n_1 p_1 (1 - e^{-x_1}) + n_2 p_2 (1 - e^{-\frac{E - n_1 x_1}{n_2}}) \\ \text{Subject} & n_1 x_1 + n_2 x_2 \leq E \\ & 0 \leq x_1 \\ & 0 \leq x_2. \end{array}$$

To solve this take the partial derivative of  $L$  with respect to  $x_1$  and set equal to zero,

$$\frac{\partial L}{\partial x_1} = p_1 h_1(x_1) - p_2 h_2\left(\frac{E - n_1 x_1}{n_2}\right) = 0$$

$$p_1 e^{-x_1} = p_2 e^{-\left(\frac{E - n_1 x_1}{n_2}\right)}.$$

Since the second derivative,

$$\frac{\partial^2 L}{\partial x_1^2} = -p_1 e^{-x_1} - \frac{n_1 p_1}{n_2} e^{-\left(\frac{E - n_1 x_1}{n_2}\right)},$$

is always less than zero, then the value obtained for  $x_1$  is indeed a maximum.

Solving for  $x_1$ ,

$$x_1^* = \frac{E - n_2 \ln\left(\frac{p_2}{p_1}\right)}{n_1 + n_2}.$$

and substituting in the appropriate values from Figure 7,

$$\frac{p_1}{p_2} = \frac{\left(\frac{20}{5365}\right)}{\left(\frac{75}{7962}\right)} = 0.3957.$$

and

$$\begin{aligned} x_1^* &= \frac{10000 - 5365 \ln(0.3957)}{7962 + 5365} \\ &= 1.12. \end{aligned}$$

Solving for  $x_2$ ,

$$\begin{aligned} x_2^* &= \frac{10000 - 7962(1.12)}{5365} \\ &= 0.20. \end{aligned}$$

Substituting these values back into the original equation yields an optimal solution whose objective function value is 54.1 launchers found out of 95 total. Since the exponential distribution is a concave function, then evenly dividing search effort among cells of the same region yields the unique optimal solution. Therefore,  $q_1 = 1 - 0.569d$  which for the same value of  $d$  as in the uniform case yields a greater reduction in  $q_1$ . Again, confidence limits can be placed on this optimal solution if all the  $L_i$  are assumed to be independent



in addition to the previous assumptions that all the  $x_i$  and  $p(i)$  are equal for each region. With these assumptions  $L$  is binomial with parameters  $n$  and  $H(x)p$  where  $E[L]=nH(x)p$  and  $Var[L]=nH(x)(1-H(x))p$ . So in regions  $G_1$  and  $G_2$  the distributions are binomial with parameters  $B(n_1=7962, H_1(x)p_1=0.00635)$  and  $B(n_2=5365, H_2(x)p=0.000665)$  respectively. Since  $n$  is large and  $H(x)p$  is small, these two distributions can now be approximated by the Poisson distribution with parameters  $P(50.53)$  and  $P(3.569)$  respectively, with a summed value of  $P(54.1)$ . This in turn can be approximated by the normal with parameters  $N(\mu=54.1, \sigma=54.1)$ . The 95% confidence limits for the normal are readily calculable, resulting in bounds of  $39.7 < L < 68.5$ .

By design  $p_1 > p_2$ , so  $p_2/p_1 < 1$  and  $\ln(p_2/p_1) < 0$ . Therefore, the ranges of  $x_1$  and  $x_2$  are

$$\frac{E}{n_1 + n_2} \leq x_1^* \leq \frac{E}{n_1}$$

$$0 \leq x_2^* < \frac{E}{n_1 + n_2} .$$

When the ratio  $p_2/p_1$  falls below 0.368 ( $\ln 0.368 = -1$ ), all the search effort is allocated to region  $G_1$  and  $x_1$  reaches its maximum value of  $E/n_1$ . Above 0.368 the value of  $x_1$  continues to decrease in accordance with its formula. As the ratio  $p_2/p_1$  approaches 1.0, the value of  $x_1$  approaches its minimum value of  $E/(n_1 + n_2)$ . Therefore, this model is insensitive to changes in intelligence estimates as long as the ratio of  $p_2$  to  $p_1$  remains below 0.368. Below this level the strategy of allocating all the search effort to region  $G_1$  is constant. Above this level the values of  $x_1$  and  $x_2$  are defined by their respective equations and change as  $p_1$  and  $p_2$  change.

### c. The Gamma Case

If the search time distribution is assumed to be Gamma, then

$$H_1(x) = \int \frac{\lambda^n x^{n-1} e^{-\lambda x}}{(n-1)!} dx,$$

and

$$E[X] = \frac{n}{\lambda}.$$

As in the previous cases assume  $E[X] = 1$  minute, which implies  $\lambda = n$ . Let their values both be 2. In addition, let  $p_3$  again be assigned the value of zero.

As in the exponential case express  $x_2$  in terms of  $x_1$  and the problem becomes

$$\begin{aligned} \text{Maximize } L &= n_1 p_1 \int 4 x_1 e^{-2x_1} dx_1 + n_2 p_2 \int 4 \left( \frac{E - n_1 x_1}{n_2} \right) e^{-2 \left( \frac{E - n_1 x_1}{n_2} \right)} dx_1 \\ \text{Subject } n_1 x_1 + n_2 x_2 &= E \\ x_1 &> 0 \\ x_2 &> 0. \end{aligned}$$

Take the partial derivative with respect to  $x_1$  and set this equal to zero. This yields

$$p_1 4 x e^{-2x} = p_2 4 \left( \frac{E - n_1 x}{n_2} \right) e^{-2 \left( \frac{E - n_1 x}{n_2} \right)}.$$

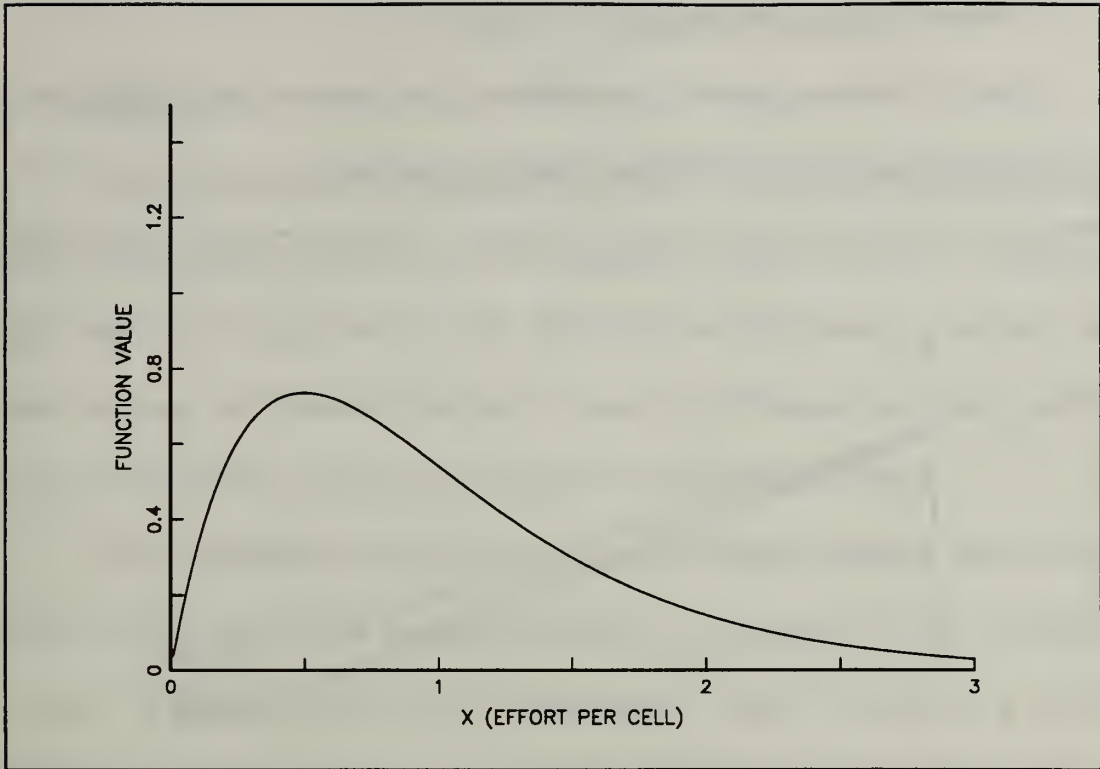
This is a transcendental equation which can only be solved by numerical approximation.

This process can just as easily be done on the original equation. Substituting in the appropriate values from Figure 7 and working through several combinations of values for  $x_1$  and  $x_2$  reveals  $L$  reaches its maximum when  $x_1$  is allowed to reach its maximum. This is revealed in the following examples:

- (1) For  $x_1 = 1.0$  and  $x_2 = 0.38$ ,  $L = 48.98$ .

- (2) For  $x_1 = 1.1$  and  $x_2 = 0.23$ ,  $L = 50.38$ .
- (3) For  $x_1 = 1.2$  and  $x_2 = 0.083$ ,  $L = 52.18$ .
- (4) For  $x_1 = 1.256(\text{max})$  and  $x_2 = 0$ ,  $L = 53.63$ .

Therefore,  $q_1=1-0.565d$  and in the case where  $E = 10,000$  minutes the optimal solution is achieved by placing all the search effort into region  $G_1$ . Similarly to the uniform and exponential cases,  $L$  is again binomial and can be approximated by a normal distribution with a 95% confidence interval of  $39.3 < L < 67.0$ . However, a quick glance at the plot of the function being integrated (shown in Figure 9) reveals significantly diminishing returns from increased input of effort past a value of 2.0 (over 90% of the area under the curve is contained between 0 and 2). It must also be remembered that  $x_1$  and  $x_2$  are each governed by identical integrals multiplied by scale factors of 75 and 25 respectively. So, if the amount of total search effort  $E$  is increased enough to allow  $x_1$  to take on larger values, then it is obvious from Figure 10 that at some point it will become advantageous to put effort into region  $G_2$ .



**Figure 10.** Plot of the function  $y = 4xe^{-2x}$ .

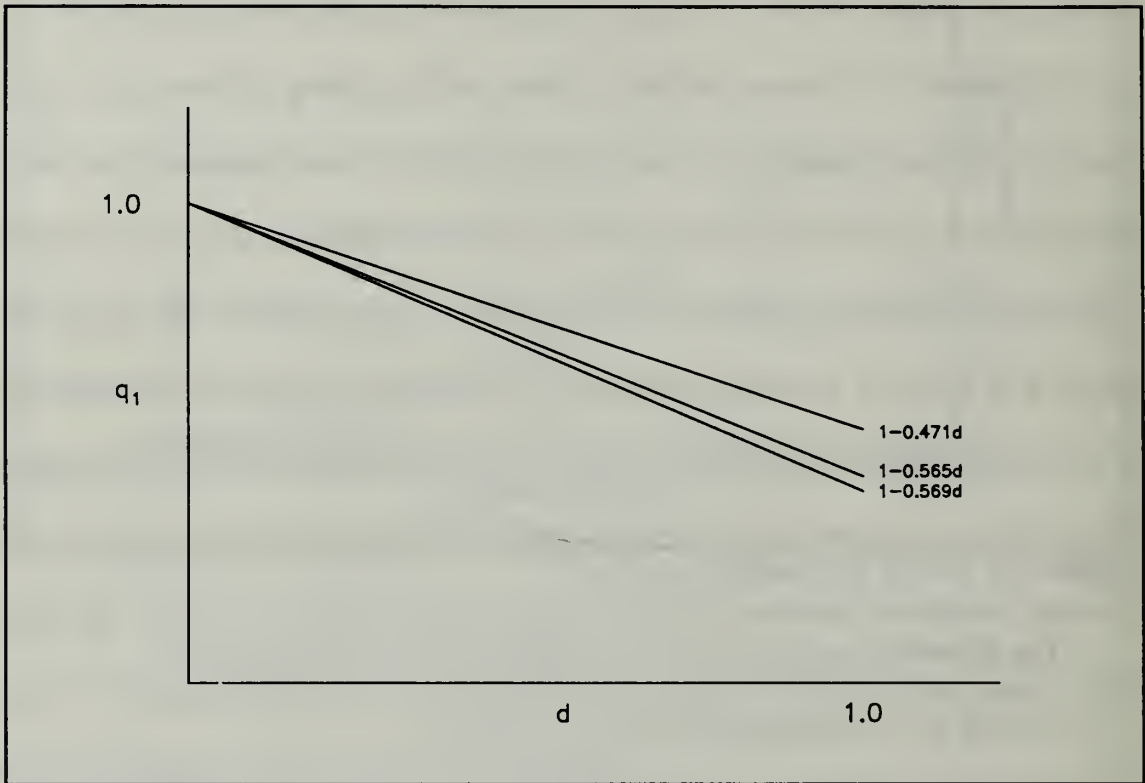
The following examples with  $E = 30,000$  reveal this to be the case:

- (1) For  $x_1 = 3.77(\text{max})$  and  $x_2 = 0$ ,  $L = 74.66$ .
- (2) For  $x_1 = 3.0$  and  $x_2 = 1.14$ ,  $L = 90.3$ .
- (3) For  $x_1 = 2.5$  and  $x_2 = 1.88$ ,  $L = 94.19$ .
- (4) For  $x_1 = 2.4$  and  $x_2 = 2.03$ ,  $L = 94.24$ .
- (5) For  $x_1 = 2.3$  and  $x_2 = 2.17$ ,  $L = 94.04$ .

It is clear from these examples the optimal solution is reached between (3) and (4). It suffices to say that the relationship between the total search effort  $E$  and its allocation ( $x_1$  and  $x_2$ ) is a complex one, but for any value of  $E$  the approximate values of  $x_1$  and  $x_2$  that yield the optimal solution can be calculated numerically.

## 2. Search Strategy Results

Figure 11 shows a graphical representation of the reduction in  $q_l$  achievable by each of the three search time distribution functions examined.



**Figure 11.** Graph of  $q_l$  reduction.

It is apparent from this graph the value of  $q_l$  depends on  $d$  as well as the choice of a distribution function launcher find time. Note that for the distribution function chosen the slope of the lines are approximately the same.



## **V. CONCLUSION**

### **A. SUMMARY**

Search theory provides a systematic approach to locating and interdicting mobile tactical ballistic missiles and their associated transporter erector launchers. If effectively implemented it can significantly reduce the search area by eliminating regions where mobile launchers are extremely unlikely to venture either because of terrain conditions and road accessibility or proximity to storage and maintenance facilities.

Using unclassified terrain data in the form of Defense Mapping Agency digital terrain elevation data and the programs contained in the appendix, several examples of the power of negative search theory are presented. Figure 7 is used as a basis for extracting real-world numbers for use in the allocation of search effort. Several distribution functions are used to illustrate the search time distribution needed for optimal allocation of total search effort. None of these probably represent the true distribution. However, in the absence of any hard data from actual testing with aircraft and simulated mobile launchers performed in the proper environment they provide the only tool for examining how best to allocate search effort to the different regions created through the use of a negative search algorithm and presented in the form of probability maps.

### **B. POSSIBLE FOLLOW-ON RESEARCH**

Two possible avenues for further research are: development of a post-launch search strategy based on rocket plume location; and enhanced realism of the terrain/road factor probability maps.

The development of an effective post-launch search strategy to locate and interdict mobile launchers after they have fired a missile by use of rocket plume location cuing would be invaluable in providing the counterforce threat needed to deter a potential enemy from attempting a launch. Figure 8 provides an example of how this strategy could be formed. Using infra-red reconnaissance satellites to geo-locate the site of missile launch within one of the 1km grid squares and intelligence information on the speed with which the mobile launchers can dismantle and move, a time can be estimated for the gathering of this information, its dissemination to an orbiting attack aircraft, and its transit to the launch site. This time can then be used to create an area within which the mobile launcher is known with certainty. Negative search theory can then be applied to this much smaller region to eliminate terrain that would slow the launcher's movement.

Figure 8 shows a scenario in which three TBMs are simultaneously launched from different locations within Libya. The time from missile launch until an aircraft arrives is assumed to be 30 minutes, while the dismantle time for the launcher is assumed to be 15 minutes. Thus the launcher has 15 minutes of movement before the search aircraft arrives. If the mobile launcher's speed is 20kph, then it could travel 5km within 15 minutes. The purple areas represent areas where a mobile launcher could have travelled in this time exclusive of those areas ruled out by a negative search.

Enhanced realism of the probability maps created by eliminating areas of low probability and highlighting areas of high probability is the other avenue of approach. The database used to create the maps could be expanded to include such factors as vegetation and soil composition (i.e. sand, swamp, hard packed earth) to reduce the search

area further. It could also include communication nodes, highway overpasses, caves and other significant features to highlight areas for closer scrutiny.

This list is not meant to be all-inclusive. TBM location is an emerging problem with many possibilities. This thesis merely brushes the surface of that problem, one that will probable be with us for some time to come.

## APPENDIX

The appendix contains the computer programs that were used to create the color grid maps of the Tripoli, Libya area. An explanation of each program and additional clarifying comments are contained within each program.

### A. PROGRAM 1

This program is designed to read in DMA DTED data for one kilometer spot elevations in the Tripoli, Libya area. For each square kilometer grid it will take the corner elevations and calculate an approximate slope. Standard deviation will give a good approximation of the relative flatness of the terrain obtained within each grid square. Input will consist of a matrix of 0..3 values representing the slope for each square.

KEY: 0 = WATER AREAS  
1 = LAND AREAS WITH  $\leq 3\%$  SLOPE  
2 = LAND AREAS WITH  $3\% < \text{SLOPE} < 6\%$   
3 = LAND AREAS WITH  $\geq 6\%$  SLOPE

USES DOS;

CONST Xsize = 240;  
Ysize = 32;

TYPE SumPtr = ^Real;  
ElevPtr = ^Word;  
Earray = array [0..Xsize,0..Ysize] of ElevPtr;  
Sarray = array [0..Xsize,0..Ysize] of SumPtr;

VAR Ymin,Ymax,Xmin,Xmax : Byte;  
counter,i,j,x: Integer;  
ELEV: Earray;  
SUM: Sarray;  
DataIn,DataOut : Text;

This procedure takes the spot elevations from the array ELEV[i,j], calculates the slope of each grid square and assigns it to the array SUM[i,j].

PROCEDURE Grad;

```
VAR Mu: Real;
BEGIN
  FOR j:= Ymin to (Ymax - 1) DO
    BEGIN
      FOR i:= 0 to (Xsize - 1) DO
        BEGIN
          NEW(SUM[i,j]);
          Mu:= (ELEV[i,j]^ + ELEV[i+1,j]^
            + ELEV[i,j+1]^ + ELEV[i+1,j+1]^)/4;
          Ex2:= (SQR(ELEV[i,j]^) + SQR(ELEV[i+1,j]^)
            + SQR(ELEV[i,j+1]^) + SQR(ELEV[i+1,j+1]^))/4;
          SUM[i,j]^:= SQRT(Ex2 - SQR(Mu));
        END;
      END;
    END;{Grad}
```

This procedure takes the slope values from the array SUM[i,j] and assigns them to the terrain categories 0..3.

PROCEDURE Color;

```
BEGIN
  FOR j:= Ymin to (YMax-1) DO
    BEGIN
      FOR i:= 0 to (Xsize-1) DO
        BEGIN
          IF (SUM[i,j]^ = 0.0) AND (ELEV[i,j]^ = 0) THEN
            SUM[i,j]^:= 0.0;
          IF (SUM[i,j]^ = 0.0) AND (ELEV[i,j]^ <> 0) THEN
            SUM[i,j]^:= 1.0;
          IF (SUM[i,j]^ <= 15.0) AND (SUM[i,j]^ > 0.0) THEN
            SUM[i,j]^:= 1.0;
          IF (SUM[i,j]^ > 15.0) AND (SUM[i,j]^ <= 30.0) THEN
            SUM[i,j]^:= 2.0;
          IF SUM[i,j]^ > 30.0 THEN
            SUM[i,j]^:= 3.0;
          IF (i > 0) AND (j > 0) AND (SUM[i,j]^ = 1.0) AND
            (((SUM[i-1,j]^ > 1.0) AND (SUM[i+1,j]^ > 1.0)) OR
            ((SUM[i,j-1]^ > 1.0) AND (SUM[i,j+1]^ > 1.0)))
```



```

        THEN SUM[i,j]^:= 3.0;
    END;
END;
END;{ Color}

```

This procedure reads in the elevation readings from the datafile.

```

PROCEDURE ReadInfile;

BEGIN
    Writeln(counter);
    FOR j:= Ymin to YMax DO
        BEGIN
            FOR i:= 0 to XSize DO
                BEGIN
                    READ(DataIn,x);
                    New (ELEV[i,j]);
                    ELEV[i,j]^ := x;
                END;
            Readln(DataIn);
        END;
    END;{ ReadInFile}

```

This procedure purges array space so that Pascal variable limits are not exceeded while also sending the results to an output file.

```

PROCEDURE Trash;

BEGIN
    FOR j:= Ymin to (YMax-1) DO
        FOR i:= 0 to (XSize-1) DO
            Dispose(ELEV[i,j]);
        FOR j:= Ymin to (YMax-1) DO
            BEGIN
                FOR i:= 0 to (XSize -1) DO
                    BEGIN
                        WRITE(DataOut,TRUNC(SUM[i,j]^:2);
                        Dispose(SUM[i,j]);
                    END;
                WRITELN(DataOut);
            END;
        END;
    END;

```



```

BEGIN{main program}
  ASSIGN(DataOut,'a:MAP.OUT');
  ASSIGN(DataIn,'a:datafil1.ibm');
  RESET(DataIn);
  REWRITE(DataOut);
  Ymin := 0;
  Ymax := YSize;

```

A counter is used to take the input datafile in 3 discrete chunks so as not to exceed Pascal's array variables limit.

```

FOR counter := 1 to 3 DO
  BEGIN
    ReadinFile;
    Grad;
    Color;
    Trash;
    Ymin := Ymin + 30;
    Ymax := YMax + 30;
  END;
CLOSE(DataOut);
END.{THESIS01}

```

## B. PROGRAM 2

This C program is designed to take as its input the array SUM[i,j] that was created in Program 1 and create a colored grid map from the gradient values 0,1,2,3 and road type values 4,5 that were manually overlayed onto SUM[i,j].

```
#include <stdio.h>
#include <strings.h>
#include <gl/gl.h>
short a[96][240];
#define INPUT "rgmap.out"
#define WINHEIGHT 475
#define WINWIDTH 1200
long MapWindow;
```

```
main()
{
```

This section of code opens the input file, initializes the the array coordinate markers, and assigns case values to the input file values.

```
    int i,j,k;
    char tempstr[1028];
    FILE *fp;
    int ypos,xpos;
    i = 0;
    j = 0;
    fp = fopen(INPUT,"r");
    while ((k = getc(fp)) != EOF)
    {
        switch (k)
        {
            case '0':
                a[i][j]= 0;
                j++;
                break;
            case '1':
                a[i][j]= 1;
                j++;
                break;
            case '2':
                a[i][j]= 2;
                j++;
                break;
```

```

    case '3':
        a[i][j]= 3;
        j++;
        break;
    case '4':
        a[i][j]= 4;
        j++;
        break;
    case '5':
        a[i][j]= 5;
        j++;
        break;
    case '6':
        a[i][j]= 6;
        j++;
        break;
    case '\n':
        i++;
        j=0;
        break;
    default:
        break;
}
}

```

This section of code opens and labels the map window, establishes its location on the screen, and assigns it an initial color of blue.

```

preposition(40,40+WINWIDTH,200,200+WINHEIGHT);
MapWindow = winopen("ATLAS TEST");
wintitle("Road/Gradient Map -- Tripoli Area ");
shademodel(FLAT);
color(BLUE);
writemask(4095);
clear();

ypos = WINHEIGHT;
xpos = 0;

```

This section of code cycles through every array position assigning colors based on slope and road type, thus creating the initial probability map with road network overlay.

```

for (i = 0; i < 96; i++)

```

```

{
    for (j = 0; j <240; j++)
    {
        if (a[i][j]== 0)
            color(138);
        else if (a[i][j]== 1)
            color(133);
        else if (a[i][j]== 2)
            color(83);
        else if (a[i][j]== 3)
            color(74);
        else if (a[i][j]== 4)
            color(80);
        else if (a[i][j]== 5)
            color(80);
    }
}

```

This section of code checks all grid squares with less than 6% slope (i.e. terrain values 1 or 2) to see if there is a road within 5km. If there is, it then assigns the grid square the color red signifying a high probability area. The code can be amended to check only areas of less than 3% slope also. Due to limitations in the size of IF statements allowed by C, they had to be broken into smaller segments.

```

if (((a[i][j]==1)||(a[i][j]==2))&&
    ((a[i+1][j]==5)||(a[i-1][j]==5)||
    (a[i][j+1]==5)||(a[i][j-1]==5)||
    (a[i+2][j]==5)||(a[i-2][j]==5)||
    (a[i][j+2]==5)||(a[i][j-2]==5)||
    (a[i+3][j]==5)||(a[i-3][j]==5)||
    (a[i][j+3]==5)||(a[i][j-3]==5)||
    (a[i+4][j]==5)||(a[i-4][j]==5)||
    (a[i][j+4]==5)||(a[i][j-4]==5)||
    (a[i+5][j]==5)||(a[i-5][j]==5)||
    (a[i][j+5]==5)||(a[i][j-5]==5)||
    (a[i+1][j]==4)||(a[i-1][j]==4)||
    (a[i][j+1]==4)||(a[i][j-1]==4)||
    (a[i+2][j]==4)||(a[i-2][j]==4)||
    (a[i][j+2]==4)||(a[i][j-2]==4)||
    (a[i+3][j]==4)||(a[i-3][j]==4)||
    (a[i][j+3]==4)||(a[i][j-3]==4)||
    (a[i+4][j]==4)||(a[i-4][j]==4)||
    (a[i][j+4]==4)||(a[i][j-4]==4)||
    (a[i+5][j]==4)||(a[i-5][j]==4))))
    color(80);
if (((a[i][j]==1)||(a[i][j]==2))&&

```

```

((a[i+1][j+1]==5)||a[i-1][j-1]==5)||
(a[i-1][j+1]==5)||a[i+1][j-1]==5)||
(a[i+2][j+2]==5)||a[i-2][j-2]==5)||
(a[i-2][j+2]==5)||a[i+2][j-2]==5)||
(a[i+3][j+3]==5)||a[i-3][j-3]==5)||
(a[i-3][j+3]==5)||a[i+3][j-3]==5)||
(a[i+4][j+4]==5)||a[i-4][j-4]==5)||
(a[i-4][j+4]==5)||a[i+4][j-4]==5)||
(a[i+5][j+5]==5)||a[i-5][j-5]==5)||
(a[i-5][j+5]==5)||a[i+5][j-5]==5)||
(a[i+1][j+1]==4)||a[i-1][j-1]==4)||
(a[i-1][j+1]==4)||a[i+1][j-1]==4)||
(a[i+2][j+2]==4)||a[i-2][j-2]==4)||
(a[i-2][j+2]==4)||a[i+2][j-2]==4)||
(a[i+3][j+3]==4)||a[i-3][j-3]==4)||
(a[i-3][j+3]==4)||a[i+3][j-3]==4)||
(a[i+4][j+4]==4)||a[i-4][j-4]==4)))
(a[i-4][j+4]==4)||a[i+4][j-4]==4)))

```

```
color(80);
```

```

if (((a[i][j]==1)||a[i][j]==2))&&
((a[i-4][j+3]==5)||a[i-3][j+4]==5)||
(a[i+4][j+3]==5)||a[i+3][j+4]==5)||
(a[i+3][j-4]==5)||a[i+4][j-3]==5)||
(a[i-3][j-4]==5)||a[i-4][j-3]==5)||
(a[i-4][j+3]==4)||a[i-3][j+4]==4)||
(a[i+4][j+3]==4)||a[i+3][j+4]==4)||
(a[i+3][j-4]==4)||a[i+4][j-3]==4)||
(a[i-3][j-4]==4)||a[i-4][j-3]==4)||
(a[i-2][j+3]==5)||a[i-3][j+2]==5)||
(a[i+3][j+2]==5)||a[i+2][j+3]==5)||
(a[i+2][j-3]==5)||a[i+3][j-2]==5)||
(a[i-3][j-2]==5)||a[i-2][j-3]==5)||
(a[i-2][j+3]==4)||a[i-3][j+2]==4)||
(a[i+3][j+2]==4)||a[i+2][j+3]==4)||
(a[i+2][j-3]==4)||a[i+3][j-2]==4)||
(a[i-3][j-2]==4)||a[i-2][j-3]==4)))

```

```
color(80);
```

```

if (((a[i][j]==1)||a[i][j]==2))&&
((a[i-5][j+4]==5)||a[i-4][j+5]==5)||
(a[i+4][j+5]==5)||a[i+5][j+4]==5)||
(a[i+5][j-4]==5)||a[i+4][j-5]==5)||
(a[i-4][j-5]==5)||a[i-5][j-4]==5)||
(a[i-5][j+4]==4)||a[i-4][j+5]==4)||
(a[i+4][j+5]==4)||a[i+5][j+4]==4)||

```

```

(a[i+5][j-4]==4)||(a[i+4][j-5]==4)||
(a[i-4][j-5]==4)||(a[i-4][j-5]==4)))
    color(80);

```

This section of code fills in isolated flat spots (i.e. areas with terrain factor 1 or 2 surrounded by areas with terrain factor 2 or 3).

```

if (((a[i][j]==1)||(a[i][j]==2))&&
    (((a[i+2][j]==3)||(a[i+2][j]==2))&&
    ((a[i-2][j]==3)||(a[i-2][j]==2))&&
    ((a[i][j+2]==3)||(a[i][j+2]==2))&&
    ((a[i][j-2]==3)||(a[i][j-2]==2))))
    color(133);

```

This statement gets rid of the wrap-around effect on the left hand edge caused by roads being present on the right hand edge.

```

if ((j<6)&&(i>40)&&((a[i][j]==1)||(a[i][j]==2)))
    color(133);

```

These statements are examples of rocket plume location.

```

if ((i>=16)&&(j>=140)&&(i<=18)&&(j<=142))
    color(194);
if ((i>=63)&&(j>=77)&&(i<=65)&&(j<=79))
    color(194);
if ((i>=89)&&(j>=206)&&(i<=91)&&(j<=208))
    color(194);

```

These statements increment the size of the grid squares.

```

    rectf(xpos,ypos,xpos+5,ypos-5);
    xpos += 5;
}
ypos -=5;
xpos = 0;
}
sleep(300);
}

```



## LIST OF REFERENCES

1. Ehlers, M.A., Master's Thesis, Naval Postgraduate School, Monterey, California, September 1992.
2. Defense Mapping Agency, *Digital Terrain Elevation Data*, 1992.

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